

Precision Measurements of Absorption and Refractive-Index Using an Atomic Candle

20 March 2002

Prepared by

T. SWAN-WOOD, J. G. COFFER, and J. C. CAMPARO
Electronics and Photonics Laboratory
Laboratory Operations

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE SPACE COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

20020422 241

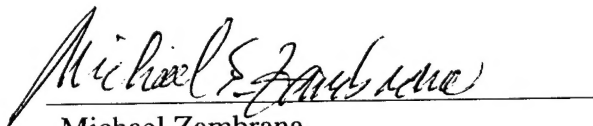
Engineering and Technology Group

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-00-C-0009 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Los Angeles Air Force Base, CA 90245. It was reviewed and approved for The Aerospace Corporation by B. Jaduszliwer, Principal Director, Electronics and Photonics Laboratory. Michael Zambrana was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

A handwritten signature in cursive script, reading "Michael E. Zambrana", is written over a horizontal line.

Michael Zambrana
SMC/AXE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</small>					
1. REPORT DATE (DD-MM-YYYY) 20-03-2002		2. REPORT TYPE		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Precision Measurements of Absorption and Refractive-Index Using an Atomic Candle				5a. CONTRACT NUMBER F04701-00-C-0009	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) T. Swan-Wood, J. G. Coffey, and J. C. Camparo				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation Laboratory Operations El Segundo, CA 90245-4691				8. PERFORMING ORGANIZATION REPORT NUMBER TR-99(8555)-11	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Space and Missile Systems Center Air Force Space Command 2450 E. El Segundo Blvd. Los Angeles Air Force Base, CA 90245				10. SPONSOR/MONITOR'S ACRONYM(S) SMC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) SMC-TR-02-18	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Across a broad range of disciplines, the accurate determination of an electromagnetic wave's amplitude (either absolute or relative) has considerable relevance. Here, we demonstrate a novel and potentially very precise method for making intensity measurements based on the atomic stabilization of electromagnetic field-strength. For ease of reference, and by analogy to atomic clocks, we refer to this field-strength stabilization system as an atomic <i>candle</i> . While the candle's original purpose was to create a field with long-term intensity stability, its very nature makes it ideal for detecting subtle amplitude changes in strong electromagnetic fields, a problem that is fundamentally different from detecting weak signals in the presence of noise. In this paper, we discuss proof-of-principle experiments demonstrating the atomic candle's ability to make precise measurements of absorption coefficients and indices of refraction.					
15. SUBJECT TERMS Absorption coefficient, Amplitude stabilization, Atomic candle, Atomic clocks, dielectric constant, Index of refraction, Magnetic resonance					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON James Camparo
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER (include area code) (310)336-6944

Note

The material reproduced in this report originally appeared in *IEEE Transactions on Instrumentation and Measurement*. The TR is published to document the work for the corporate record.

IEEE Transactions on Instrumentation and Measurement, Vol. 50, No. 5, October 2001.
© copyright 2001 IEEE.

Precision Measurements of Absorption and Refractive-Index Using an Atomic Candle

Tabitha Swan-Wood, John G. Coffer, and James C. Camparo

Abstract—Across a broad range of disciplines, the accurate determination of an electromagnetic wave's amplitude (either absolute or relative) has considerable relevance. Here, we demonstrate a novel and potentially very precise method for making intensity measurements based on the atomic stabilization of electromagnetic field-strength. For ease of reference, and by analogy to atomic clocks, we refer to this field-strength stabilization system as an atomic candle. While the candle's original purpose was to create a field with long-term intensity stability, its very nature makes it ideal for detecting subtle amplitude changes in strong electromagnetic fields, a problem that is fundamentally different from detecting weak signals in the presence of noise. In this paper, we discuss proof-of-principle experiments demonstrating the atomic candle's ability to make precise measurements of absorption coefficients and indices of refraction.

Index Terms—Absorption coefficient, amplitude stabilization, atomic candle, atomic clocks, dielectric constant, index of refraction, magnetic resonance.

I. INTRODUCTION

THE "SIMPLE" measurement of electromagnetic intensity is fundamental for much of experimental science. For example, in quantum optics, the QED interaction between a colored vacuum and a quantum system can be probed by examining the intensity of light transmitted through a high- Q cavity [1]. In atomic physics, the transmission of light through a resonant vapor can be used to measure atomic collision cross sections [2], while in analytical chemistry, transmitted light can reveal the presence of trace compounds [3]. New means for precisely measuring both the relative and absolute strength of an electromagnetic field, especially ones with advantageous and unique characteristics, are therefore of considerable relevance for a great many researchers.

We recently demonstrated that it is possible to actively stabilize the amplitude of an electromagnetic field to an atomic Rabi-resonance in much the same way as the frequency of a field is locked to a resonance between energy eigenstates in an atomic clock [4]. For ease of reference, and because of its analogy with the atomic clock, we refer to a field stabilized in this fashion as an "atomic candle." With regard to intensity measurements, the electromagnetic wave produced by an atomic candle has at

least two unique characteristics. First, the field-amplitude of the atomic candle is essentially referenced to a dressed-atom energy level transition; hence, different candles at remote locations can produce fields with the exact same intensity. Additionally, the long-term intensity stability of the field produced by the candle has the potential for atomic-clock-like performance [5].

The atomic candle's operation derives from the response of a quantum system to a modulated field; specifically, when an atom interacts with a phase-modulated resonant field, the atomic system's population oscillates at twice the phase-modulation frequency $2\nu_m$ [6]. Of importance for the atomic candle is the fact that the amplitude of these population oscillations is a resonant function of field-strength, reaching a maximum when the Rabi frequency associated with the atomic transition matches $2\nu_m$. This resonant behavior of the oscillation's amplitude is what is meant by a Rabi-resonance, and with its observation comes an ability to lock the Rabi frequency (i.e., the field-strength) to $2\nu_m$ via an atomic signal.¹

Our primary motivation in developing the atomic candle was to ameliorate a problem with the long-term stability of gas-cell atomic clocks [7], and to this end we constructed a microwave candle based on the ground state hyperfine transition of Rb^{87} at 6834.7 MHz [5]. Our atomic candle's microwave power stability for averaging times τ greater than 10 s is $\sigma_{\Delta P/P}(\tau) = 9 \times 10^{-7} + 10^{-7} \sqrt{\tau}$, where $\sigma_{\Delta P/P}^2$ is the Allan variance [8] of the power fluctuations relative to the Rabi-resonance peak. In order to achieve this tight lock, it is necessary for the atomic candle to detect and respond to very small changes in field intensity. Typically, these changes are stochastic in nature. However, they could just as well be deterministic and under experimental control, in which case the candle would provide a sensitive detector of subtle field-strength changes. As a proof-of-principle experiment to illustrate this potential, we have used the field of our microwave atomic candle to measure the absorption coefficient and refractive index of liquid water and acetone at 6.8 GHz.

II. EXPERIMENT

A. The Atomic Candle

Fig. 1 shows a schematic outline of our experimental arrangement, where open boxes correspond to the atomic candle proper. The heart of our candle is a resonance-cell containing isotopically pure Rb^{87} and 100 Torr of N_2 placed in the vicinity of a microwave horn. As illustrated in Fig. 2, the microwaves are resonant with the $(F = 2, m_F = 0) - (1, 0)$ ground state

Manuscript received June 19, 2000; revised May 3, 2001. This work was supported by U.S. Air Force Contract F04701-93-C-0094.

T. Swan-Wood is with the Electronics and Photonics Laboratory, The Aerospace Corporation, Los Angeles, CA 90009 USA, and also with the Materials Science Department, California Institute of Technology, Pasadena, CA 91125 USA.

J. G. Coffer and J. C. Camparo are with the Electronics and Photonics Laboratory, The Aerospace Corporation, Los Angeles, CA 90009 USA.

Publisher Item Identifier S 0018-9456(01)08761-7.

¹Note that $2\nu_m$ may be referenced to a cesium atomic clock and hence the ground state hyperfine splitting of Cs^{133} (i.e., the SI definition of the second).

photodiode/lock-in combination acts as a low-pass detector of the atoms' second harmonic signal. For the atomic candle correction signal, the microwave power is modulated at 7.3 Hz by applying a sinusoidal signal to the VCA's control voltage. The atoms' Rabi-resonance response to the modulated microwave power is monitored in a heterodyne fashion with the aid of lock-in #2, whose output becomes our field-strength correction signal. Adding this correction signal to the VCA control voltage closes the field-strength feedback control loop.

B. Measurements of Electromagnetic Field Transmission

For the absorption/refractive-index measurement portion of the experiment, the signal was chopped at 0.1 Hz prior to amplification by a second +30 dB amplifier, and following amplification the signal was again split in two. (Low-frequency chopping allowed us to discriminate against a slow baseline drift in this power-measurement portion of the experiment.) The two signals were then combined in a mixer [11], creating a dc signal whose amplitude was proportional to the power of the original microwave signal, and hence proportional to the power entering the horn.² If an attenuating material (in our case a dielectric liquid) is placed between the horn and the resonance cell, the microwave power reaching the Rb atoms will be reduced. As a consequence, the atomic candle will feed a correction signal back to the VCA that just compensates for this attenuation. The magnitude of the attenuated power is therefore detected as an *increase* in the microwave power supplied to the horn. Ideally, we would have used the correction signal from lock-in #2 to measure the microwave attenuation, as microwave power changes then appear on a near-zero signal background. This approach was problematic in our experiment due to limits in the dynamic range of the electronics associated with our VCA. However, we also felt that measuring the power supplied to the horn directly provides a cleaner demonstration of this atomic candle application.³

We employed research grade acetone and water as attenuating materials for our microwave signal. These were contained in a 14.5 cm diameter open Pyrex dish placed between the horn and the resonance cell. The dish rested on a 1.8 cm thick sheet of polyurethane microwave absorber, which had a specified microwave attenuation coefficient greater than -20 dB. The sheet was large enough to ensure that sidelobes from the horn were attenuated. A small ~3 cm² hole was cut in the sheet directly under the center of the horn, so that only microwaves incident normally to the liquid would pass into the resonance cell. During the course of the experiment, the acetone and water temperatures remained constant at 21 °C and 23 °C, respectively, with no observed rise in temperature due to microwave absorption. The liquid's depth d was determined by adding known volumes of liquid to the dish, and then correcting these depth values for loss due to evaporation.

²If V_{LO} and V_{RF} [both equal to $\sqrt{P_o} \sin(\omega t)$] are the microwave signals input to the mixer, then the mixer's output V_{IF} is just $V_{IF} = V_{LO} \cdot V_{RF} = P_o/2(1 - \cos(2\omega t))$.

³It might be argued that measuring the power supplied to the horn in the fashion of Fig. 1 does not really provide any advantage over more traditional techniques, as we are still making a conventional power measurement. However, one of the advantages associated with the atomic candle is its potential for very long-term stability. Hence, in the specific scheme of Fig. 1 the power measurement signal may be averaged over long time intervals to improve the measurement precision.

Subsequent to performing an absorption/refractive-index experiment, we measured the rate-of-change of power supplied to the horn dP/dt , resulting from evaporation alone.⁴ At fixed temperature and pressure, the rate of acetone evaporation is constant, since this primarily depends on the acetone vapor pressure just above the liquid surface. In the case of water, the rate of evaporation is also a constant, but additionally depends on the relative humidity [12]. Consequently, by noting the times of liquid addition in the present experiment, we could use the results from these subsequent experiments to correct the relative power measurements for evaporative loss.

At microwave wavelengths, macroscopic depths of liquid act as a thin film. Therefore, the power reaching the resonance cell P_{lock} (i.e., the locked power of the atomic candle) is given by [13]

$$\frac{P_o}{P_{lock}} = \frac{e^{\alpha d}}{|T|^2} \{1 + 2|R|e^{-\alpha d} \cos[4\pi nd/\lambda + \theta] + |R|^2 e^{-2\alpha d}\}. \quad (1)$$

where

P_o	measured power supplied to the horn;
R and T	parameters associated with the reflection and transmission, respectively, of the liquid at its boundaries;
θ	phase angle;
α	absorption coefficient;
n	refractive-index.

Fig. 3 shows our acetone measurements of P_o/P_{lock} as a function of d , and these are clearly consistent with (1): damped oscillations are observed to be riding on an exponentially increasing baseline. Similar results were obtained for water, except that fewer oscillations were observed. (Though water's index of refraction at 6.8 GHz is roughly twice that of acetone's, water's absorption coefficient is more than four times larger.) Thus, in the case of water we could not access as large a range of water depths as we could for acetone due to the limitations of our microwave amplifier.

III. RESULTS

Regarding Fig. 3, we infer α from the exponential increase in P_o/P_{lock} at large depths, while the wavelength of the sinusoidal variations in P_o/P_{lock} yields n . The results for acetone and water are given in Table I, along with estimates of the measurements' precision. Table I also presents theoretical estimates of α and n based on the empirical Cole-Cole equation, a modified version of the familiar Debye equation [14], [15]. Clearly, in its crudest realization for this type of measurement (i.e., an

⁴As an aside, we note that it should be possible to use the atomic candle to access the liquid's latent heat of vaporization. For example, in the case of acetone it is relatively straightforward to show that the rate of change of acetone depth d due to evaporation is related to acetone's latent heat of vaporization

$$\Delta Q_{vap} \dot{d} = B \exp \left[-\frac{\Delta Q_{vap}}{kT_{liq}} \right]$$

where B is a constant, k is Boltzmann's constant, and T_{liq} is the liquid temperature. For Beer's law absorption, where α is the absorption coefficient, $P = -\alpha d P_o e^{-\alpha d}$, so that if dP/dt is measured as a function of acetone temperature it should be possible to ascertain ΔQ_{vap} .

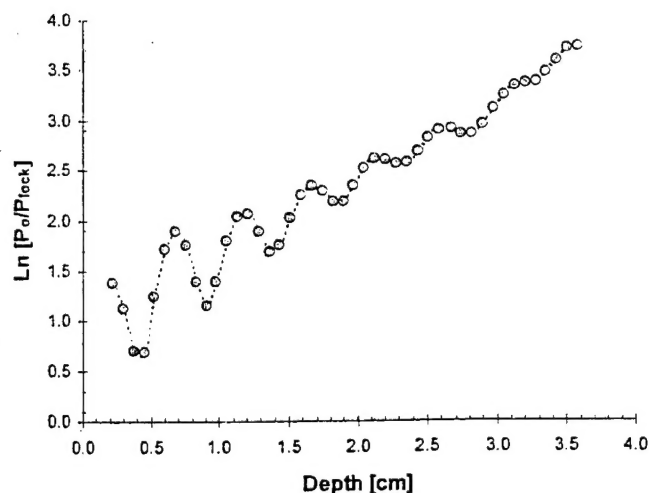


Fig. 3. Experimental results for acetone at 21 °C. Linear fit between 1.7 and 3.6 cm depths was used to determine α . After subtracting the linear slope, the oscillation wavelength yielded n . The dashed curve is simply an aid to guide the eye.

TABLE I

ABSORPTION COEFFICIENT α AND REFRACTIVE INDEX n OF LIQUID ACETONE AND WATER AT 6.8 GHz. NOTE THAT THE VALUES LISTED FOR THE EMPIRICAL COLE-COLE EQUATION ARE ESTIMATES, SINCE THE PARAMETERS EMPLOYED IN THE EQUATION ARE DEPENDENT ON TEMPERATURE AND WAVELENGTH, AND ARE THEMSELVES SUBJECT TO EXPERIMENTAL UNCERTAINTY

		α [cm ⁻¹]	n
CH ₃ COCH ₃	Atomic Candle	0.817 ± 0.026	4.623 ± 0.026
	Cole-Cole Equation	0.817	4.591
H ₂ O	Atomic Candle	4.07 ± 0.03	8.27 ± 0.09
	Cole-Cole Equation	4.12	8.45

open dish of evaporating liquid that attenuates a non-planewave microwave signal), the atomic candle has achieved excellent accuracy and precision in the determination of a complex dielectric constant. Moreover, the atomic candle did not need to be calibrated to a known standard [16]. For completeness, we note that it would be straightforward to construct candles based on the hyperfine transitions of Na²³, Rb⁸⁵, and Cs¹³³, so as to make dielectric measurements at 1.8, 3.0, and 9.1 GHz, respectively. It might even be possible to base an atomic candle on a Rydberg transition [17], where a much broader range of microwave frequencies would be accessible.

IV. DISCUSSION

At its most specific, this paper has demonstrated the use of an atomic candle for the precise measurement of a material's absorption coefficient and refractive index. Of course, generalizing this atomic candle application to the optical and infrared regime, one could imagine making precise cross section measurements for resonant transitions between atomic and molecular eigenstates, thereby obtaining very accurate information on the overlap of eigenstate wavefunctions.⁵ However, it is our

⁵The microwave absorption of acetone and water in their condensed phase is properly attributed to a relaxation effect rather than resonant absorption; see [18].

opinion that the candle's utility may extend well beyond the particular work discussed here, since we have basically demonstrated a general means for observing subtle intensity changes of an electromagnetic signal, a fundamentally different problem from that of detecting weak signals in the presence of noise.

In one possible application, a remote transmitter's output power could be detected, amplified, and made part of a local atomic candle, with the remote transmitter's output power adjusted via radio-control. Fluctuations in this atomic candle's correction signal would then provide very precise information on fluctuations in the number of scatters/absorbers along the transmitter-to-receiver propagation path. The propagation path could be terrestrial, perhaps using an optical atomic candle for environmental monitoring, or space-to-Earth. One might even envision placing two atomic candles at remote locations, with one candle transmitting a reference signal to the other. In well-known fashion, the range between the transmitter and receiver would be determined by the transmitted signal's propagation time, while Doppler shifts would provide information on the relative radial velocity. By comparing the intensity of the transmitted candle-field with the local candle-field, it might be possible to augment the range and velocity information and detect changes in the propagation geometry *transverse* to the propagation path.

It seems clear to us that with enough imagination many other atomic candle applications may be envisioned, and some of these will be much more novel than those discussed above. Consequently, we believe that the true value of the present work is not so much in describing a new means for precise absorption/refractive-index measurements, though this in itself is valuable, but rather in demonstrating the atomic candle's fundamental utility for measurement science. With the demonstration of optical and infrared atomic candles, and with a demonstration of these candles' long-term intensity stability, it is our hope that the general usefulness of atomic candles for measurement science will be realized.

REFERENCES

- [1] C. J. Hood, M. S. Chapman, T. W. Lynn, and H. J. Kimble, "Real-time cavity QED with single atoms," *Phys. Rev. Lett.*, vol. 80, no. 19, pp. 4157-4160, 1998.
- [2] N. D. Bhaskar, J. Pietras, J. Camparo, W. Happer, and J. Liran, "Spin destruction in collisions between cesium atoms," *Phys. Rev. Lett.*, vol. 44, no. 14, pp. 930-933, 1980.
- [3] K. Nakagawa, T. Katsuda, A. S. Shelkovich, M. de Labachellerie, and M. Ohtsu, "Highly sensitive detection of molecular absorption using a high finesse optical cavity," *Opt. Commun.*, vol. 107, pp. 369-372, 1994.
- [4] J. C. Camparo, "Atomic stabilization of electromagnetic field strength using Rabi resonances," *Phys. Rev. Lett.*, vol. 80, no. 2, pp. 222-225, 1998.
- [5] J. G. Coffer and J. C. Camparo, "Atomic stabilization of field intensity using Rabi resonances," *Phys. Rev. A Gen. Phys.*, vol. 62, 2000.
- [6] R. P. Frueholz and J. C. Camparo, "Underlying simplicity of atomic population variations induced by a stochastic phase-fluctuating field," *Phys. Rev. A Gen. Phys.*, vol. 54, no. 4, pp. 3499-3504, 1996.
- [7] J. C. Camparo, "Atomic stabilization of electromagnetic field-strength and the gas-cell atomic clock," in *Proc. IEEE IFCS*, Piscataway, NJ, 1998, pp. 88-94.
- [8] D. W. Allan, "Should the classical variance be used as a basic measure in standards metrology?," *IEEE Trans. Instrum. Meas.*, vol. IM-36, no. 2, pp. 646-654, 1987.
- [9] J. C. Camparo, "The diode laser in atomic physics," *Contemp. Phys.*, vol. 26, pp. 443-477, 1985.
- [10] W. Happer, "Optical pumping," *Rev. Mod. Phys.*, vol. 44, no. 2, pp. 169-249, 1972.
- [11] T. S. Laverghetta, *Practical Microwaves*. Indianapolis, IN: Sams, 1984, ch. 4.

- [12] J. P. Holman, *Heat Transfer*. New York: McGraw-Hill, 1963, ch. 11.
- [13] O. S. Heavens, *Optical Properties of Thin Solid Films*. New York: Dover, 1965, ch. 4.
- [14] J. B. Hasted, *Aqueous Dielectrics*. London, U.K.: Chapman & Hall, 1973, ch. 1.
- [15] Y. Y. Akhadov, *Dielectric Properties of Binary Solutions*. New York: Pergamon, 1980.
- [16] A. Nyshadham, C. L. Sibbald, and S. S. Stuchly, "Permittivity measurements using open-ended sensors and reference liquid calibration—An uncertainty analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 2, pp. 305–314, 1992.
- [17] M. W. Noel, W. M. Griffith, and T. F. Gallagher, "Frequency-modulated excitation of a two-level atom," *Phys. Rev. A*, vol. 58, no. 3, pp. 2265–2273, 1998.
- [18] S. G. Lipson and H. Lipson, *Optical Physics*. Cambridge, U.K.: Cambridge Univ. Press, 1969, ch. 10.
- [19] C. E. Wieman and L. Hollberg, "Using diode lasers for atomic physics," *Rev. Sci. Instrum.*, vol. 62, pp. 1–20, 1991.

Tabitha Swan-Wood received the B.S. degree in physics from the University of California, Riverside (UCR), in June 2000. She is currently pursuing the Ph.D. degree in materials science from the California Institute of Technology, Pasadena.

Her research interests have included spin glass magnetism, silicon detector development, and atomic physics. She is currently studying the vibrational entropy using inelastic neutron scattering. She has three publications from her undergraduate research.

Ms. Swan-Wood was a California Robert C. Byrd Honors Scholar (1996–2000). She received UCR's Academic Program Excellence and Research Award in 1998 and 2000. She was UCR's Dr. Robert Wild Physics Scholar (1998). She received the Rosemary S. J. Schraer Outstanding Student Commencement Award for UCR's College of Natural and Agricultural Science. Upon entering California Institute of Technology, she received the Donald S. Clark Fellowship for 2000–2001.

John G. Coffer was born in Pennsylvania in 1947. He received the B.A. degree in physics from the University of Colorado, Boulder, in 1969, and the M.S. degree in physics from the University of California, Los Angeles, in 1978.

He has been Member of Technical Staff at The Aerospace Corporation, Los Angeles, since 1979. He is interested in interferometry, spectroscopy, and laser applications in applied physics and instrumentation. Recently, he has been working in the areas of diode-laser-pumped atomic clocks and fiber-optic gyroscopes.

James C. Camparo was born in Newark, NJ, in 1956. He received the B.A. degree in physics and the Ph.D. degree in chemical physics, both from Columbia University, New York, NY, in 1977 and 1981, respectively.

In 1981, he joined The Aerospace Corporation, Los Angeles, CA, as Member of Technical Staff. Currently, he is a Senior Scientist in the Lasers and Optical Physics Department of the same company. His primary interest is in the area of quantum system interactions with stochastic fields, and how the stochastic-field/atom interaction influences the operation of precise frequency standards. His studies have included laser phase-noise to amplitude-noise conversion as mediated by resonant atomic absorption, and the role of stochastic fields in multiphoton processes. In addition to his atomic physics research, he has an interest in the design and operation of precision timekeeping systems for space applications. In support of miltatcom programs, he has created computer simulations of miltatcom timekeeping systems, and used these to investigate the performance of spacecraft timekeeping algorithms.

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Laboratory Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual organizations:

Electronics and Photonics Laboratory: Microelectronics, VLSI reliability, failure analysis, solid-state device physics, compound semiconductors, radiation effects, infrared and CCD detector devices, data storage and display technologies; lasers and electro-optics, solid state laser design, micro-optics, optical communications, and fiber optic sensors; atomic frequency standards, applied laser spectroscopy, laser chemistry, atmospheric propagation and beam control, LIDAR/LADAR remote sensing; solar cell and array testing and evaluation, battery electrochemistry, battery testing and evaluation.

Space Materials Laboratory: Evaluation and characterizations of new materials and processing techniques: metals, alloys, ceramics, polymers, thin films, and composites; development of advanced deposition processes; nondestructive evaluation, component failure analysis and reliability; structural mechanics, fracture mechanics, and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena.

Space Science Applications Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; infrared surveillance, imaging, remote sensing, and hyperspectral imaging; effects of solar activity, magnetic storms and nuclear explosions on the Earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation, design fabrication and test; environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes.

Center for Microtechnology: Microelectromechanical systems (MEMS) for space applications; assessment of microtechnology space applications; laser micromachining; laser-surface physical and chemical interactions; micropropulsion; micro- and nanosatellite mission analysis; intelligent microinstruments for monitoring space and launch system environments.

Office of Spectral Applications: Multispectral and hyperspectral sensor development; data analysis and algorithm development; applications of multispectral and hyperspectral imagery to defense, civil space, commercial, and environmental missions.